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PARTICLE DISPERSION IN A TURBULENT SPRAY

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FINAL REPORT

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University of California Davis, CA 95616.

SUMMARY

A scheme was devised to inject individual tagged droplets into a turbulent spray. The droplets were tagged with a laser dye. The bulk of the spray in the jet was created with micro air blast atomizers that formed an aerosol with a narrow size distribution. Particle Imaging Velocimetry (PIV) was implemented with a novel solid state high voltage switch to control the Pockel cell of a YAG laser. The PIV results showed that the micro atomizers yielded well behaved initial conditions for the spray. Dispersion measurements of a tagged fluorescent droplet indicated that the spray had an impact on the dispersion phenomenon if any swirl were imparted to the flow; with precisely aligned injectors the effect of the spray on particle dispersion was very small, suggesting that turbulence modulation was not important under well controlled conditions. Droplet Lasing Spectroscopy was applied successfully to measurements of vaporization rates of droplets in non reacting and in burning droplet streams. The results represented a significant extension of the lasing principle to more realistic spray conditions. Instantaneous vaporization rates were measured in a burning droplet stream where the technique was found to yield accurate data. A particle Large Eddy Simulation (PLES) sub model was implemented into a hybrid spectral - finite difference solution procedure for the Navier-Stokes equation. A semi-analytical Poisson solver was established that was accurate and fast. The PLES method showed encouraging results in jet simulations.

TECHNICAL DISCUSSION

Experiments

The guiding philosophy of the experimental program was the development of accurate data on turbulent dispersion and vaporization of particles in a shear flow with well characterized initial conditions. Atomizers that are frequently used in spray research involve rather complicated geometries and initial conditions. Considerable effort has been expended to achieve very well defined conditions that can be implemented in a LES code for comparison.

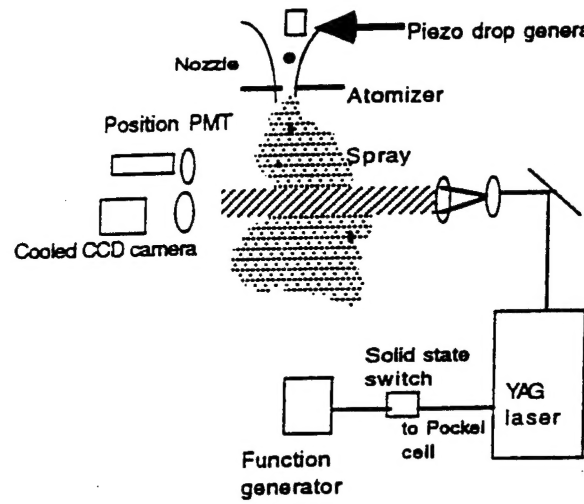

Figure 1 Experimental spray apparatus

A round turbulent jet was the base flow for the experiments. The challenge was to add a controllable spray to the flow with minimal disturbances, in order to elucidate the impact of turbulence modification on the spray behavior. Initial efforts to add the spray to the base flow ended in excessive dripping of the spray from the exit of the nozzle. The current technique uses a series of micro air blast atomizers to produce a very fine aerosol close to the nozzle exit.

The air blast atomizers yield a spray with mass loadings up to 30% with the possibility of achieving higher loadings in the future. Measurements of the dispersion of a single particle were obtained by adding a fluorescent dye to a droplet that was created by a piezo electric droplet generator. The fluorescent particle was injected along the centerline of the spray. Fluorescence that was emitted from the particle as it passed through an Argon ion laser sheet was imaged onto a position sensing photomultiplier tube. The output from the phototube was digitized and stored on a computer. Data from many particles were collected and

averaged to yield the mean square displacement from the axis, the so-called dispersion. Measurements were obtained of the dispersion of various size droplets as a function of the mass loading (mass of water per mass of air) in the spray. It was apparent that the addition of the spray had an impact on the dispersion of the tagged fluorescent particle. The *prima facie* evidence suggested that the turbulence of the base flow was modified by the liquid droplets in the flow. However, a Reynolds stress calculation of the jet flow and a stochastic calculation of the droplet motion indicated that Reynolds numbers over 100 were unlikely, too small for Hetsroni's vortex shedding mechanism to be important. A Mie scattering image (not shown) of the spray suggested an alternative explanation.

A large scale, quasi sinusoidal motion of the spray was evident in this figure. Other authors have described a similar helical mode in single phase jets in the past. It should be recalled that the exit conditions of the jet are laminar and "top hat". The amount of turbulence in the jet exit flow is small. However, jets are sensitive to small perturbations in the near field region. A potential explanation of the enhanced dispersion is suggested by this observation. That is, the stability of the jet is affected by the momentum transfer between the phases and ultimately the "helical" motion is augmented by the addition of the spray. It can also be argued that the method of spray addition contributes to additional perturbations. This question could only be answered by Planar Imaging Velocimetry (PIV) measurements at the jet exit and in the near field as the spray developed.

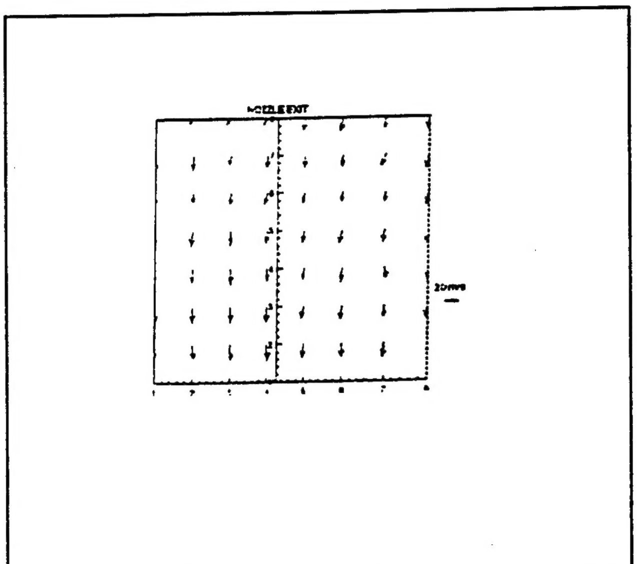

Figure 2 PIV measurements of initial exit velocity of spray

A novel scheme was implemented to obtain these PIV data with limited optical resources. A single YAG laser was used to generate the light sheet for the velocity imaging. A double pulse with variable timing was generated with a solid state switch that had been introduced to the US market. It permitted switching of the 3 to 5 kV supply to the Pockel cell of the YAG laser within 10 ns, following a TTL input signal from a function generator. Hence, a Marx bank was not required to generate the double pulse. Furthermore, the solid state switch offered flexibility in timing as well as the possibility of using multiple pulses for Particle Tracking

Velocimetry. This scheme was implemented successfully in the spray. The strong secondary background scattering from the spray outside the laser sheet necessitated image processing to remove noise via thresholding before a FFT analysis was carried out. The complete experimental set up is shown schematically in Fig. 1.

Measurements of the initial velocity field of the spray are shown in Fig. 2. Fifteen images were collected to form averages so that considerable statistical noise is included in the vectors that are shown in Fig. 2. The mean axial velocity of the spray is about 20 m s^{-1} which is approximately twice the gas phase axial velocity. The mean radial velocity of the spray is of the order of 1 m s^{-1}. The vector plot in Fig. 2 indicates that the micro atomizers produce a well behaved spray with minimal radial motion and easily characterized initial conditions that can be used in the LES. PIV data were also obtained at about 8 nozzle diameters from the jet exit. The instantaneous vector plot shows a large scale motion of the spray that lends credence to the notion that a helical structure may account for the increased dispersion of the tagged particle as spray is added to the jet.

The fabrication of the micro atomizers was subsequently improved so that their alignment with the flow was precise. The dispersion measurements were repeated over a range of spray mass loadings. The new arrangement did not exhibit the same sensitivity of dispersion of tagged droplets to spray mass loading. The results indicate that with very well controlled initial conditions turbulence modulation was not significant, even under conditions that the analysis of Crowe and co-workers would indicate the likelihood of modulation. The results serve to highlight the importance of conducting very well controlled experiments.

Droplet vaporization

The use of droplet lasing spectroscopy was examined in a water spray into which ethanol droplets were injected from a piezo electric droplet generator. The aim was to verify the feasibility of use droplet lasing in the presence of a spray. The use of water avoided the possibility of the formation of hazardous mixtures of ethanol vapor with air. The piezo electric droplet generator was used to inject single droplets of ethanol with Rhodamine 590 at concentrations of approximately $1x10^{-4}$ to $1x10^{-3}$ M along the centerline of the spray. Ethanol was used for the tagged droplet so that the vaporization rate was measurable in the near field of the jet where the vaporization was expected to be small as a result of small relative velocities between the droplets and the gas flow. All measurements were made at room temperature.

A 10 mm by 1 mm laser sheet of 532 nm radiation from a Nd:YAG laser was directed through the centerline of the jet, perpendicular to the flow direction, one diameter from the nozzle exit. The spray was run continuously at a mass loading of 20 percent. As a dye-doped droplet left the nozzle, the laser was fired. The ensuing lasing emission from the droplet was imaged with a magnification of 1/5.4 via a 50 mm lens onto the 30 micron slit of an Acton SP-150 imaging spectrograph. The focal length of the spectrograph was 150 mm. A 1200 l/mm grating was used to demonstrate the technique. A Princeton Instruments, cooled, 16 bit, 512x512 CCD camera was attached to the spectrograph.

The droplet diameter could be obtained from the emission spectrum and was dependent only on the geometry and the index of refraction as seen in Equation (1)

$$D = 2R = \frac{\lambda_n \lambda_{n+1}}{\Delta \lambda \pi} \frac{\tan^{-1}[m^2 - 1]^{1/2}}{[m^2 - 1]^{1/2}} \qquad (1)$$

where n and n+1 represent consecutive peaks in the lasing spectrum, m is the index of refraction and R is the radius of the droplet. The droplet size had no dependence on intensity as long as the peaks in the spectrum could be resolved. However, the particular approximation of Equation (1) was only valid when the droplets were round. Asphericity was not an issue in the present experiment because the Weber numbers of the droplets were

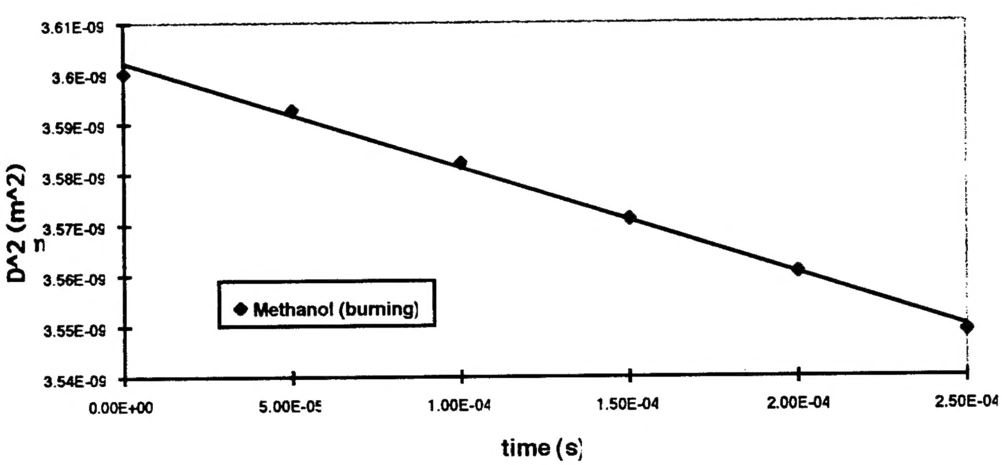

Figure 3 Burning methanol droplet showing diameter squared versus time

very small. The lasing was significantly red shifted from the Mie scattering which permitted detection against a strong background from the spray. It was also fortunate that the SRS (Stimulated Raman Scattering), which all of the droplets in the spray could exhibit, was separated significantly in wavelength (about 50 nm) from the lasing emission. The combined effects of optical filtering and the use of an imaging spectrograph permitted sizing of *only* the droplet that contained the laser dye.

The error was linear in droplet diameter so that the total error, including both the error from the peak spacing measurement and the error inherent in Equation (1), could be represented as:

$$\%\,Error = (0.1063x10^{6})D + 1 \tag{2}$$

Equation (2) provided a convenient way of estimating error. It should be noted that the error was quantifiable and known, in contrast to other methods of droplet sizing. Errors due to temperature and water content were found to be insignificant.

Vaporization Rate

As shown in the previous section, the spacing of droplet lasing peaks was sensitive to micron scale changes in droplet size. In order to measure the instantaneous vaporization rate, a more sensitive measurement was needed. As a droplet changed size, by as little as a few nanometers, the morphology dependent resonances changed position. The peak spacing stayed about the same but the individual resonances shifted to shorter wavelengths as the diameter decreased. The shift could be related to the change in radius by:

$$\frac{\Delta\lambda_{shift}}{\lambda_n} = \frac{\Delta R}{R} \tag{3}$$

Therefore, by collecting two consecutive spectra from the same droplet and measuring the shift in the spectra, the change in radius could be found. The evaporation constant could be found by knowing the time between the laser pulses.

To demonstrate this measurement, a dye-doped ethanol droplet was injected at room temperature along the centerline of the water spray. Two laser pulses from the Nd:YAG laser were separated by 100 ms. Emissions from one dye-doped droplet were imaged onto the entrance slit of the imaging spectrograph. The peaks were blue shifted 0.3 nm as a result

of droplet vaporization. An evaporation constant of 4×10^{-8} $m^2/s \pm 1.3\times10^{-8}$ m^2/s was deduced from this shift in the spectrum.

Estimation of Temperature Rise Due to Laser Excitation

It was important to estimate the amount of heating due to laser excitation. Heating by the incident light may have an impact on the vaporization rate measured by the technique. The estimated temperature rise due to laser heating was approximately 0.74 °K. This temperature rise was very small and should not have a significant effect on the droplet vaporization rate. The measured vaporization rates were compared to D^2 law predictions with good agreement (Santangelo et al., 1998).

Burning Droplets

Following the success with the application of the lasing method to an isothermal flow, attention was given to the application of DLS to burning droplets. A TSI Model 3450 vibrating orifice aerosol generator was employed to form a linear droplet stream.

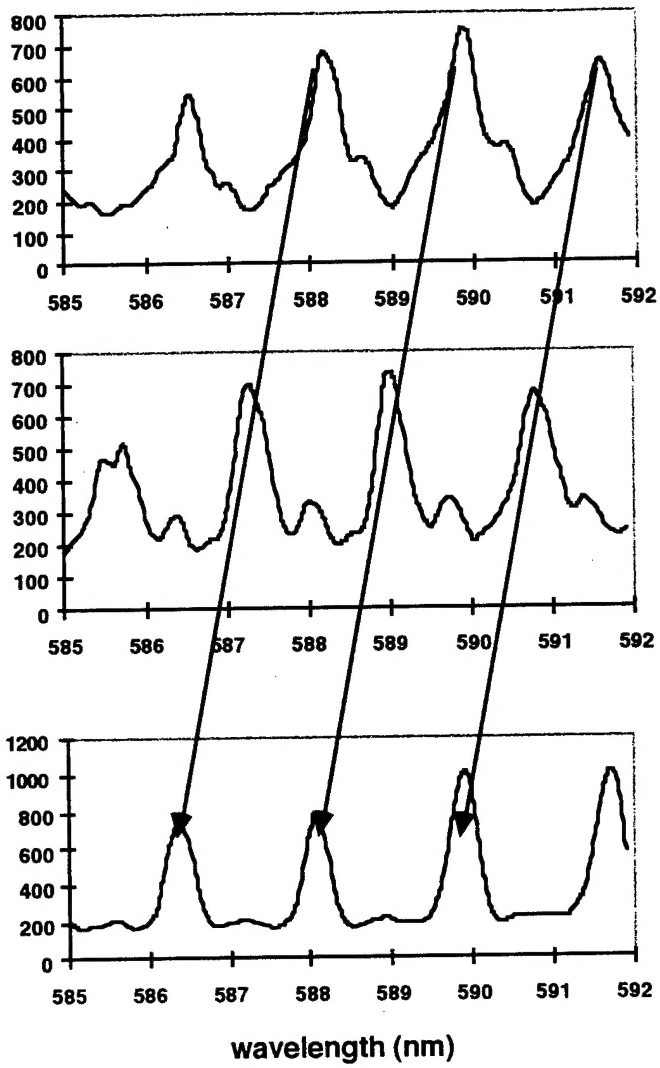

Fig. 4 Spectra from three consecutive burning methanol droplets to show shift in peaks

To the best of our knowledge, lasing spectra from *burning* droplets have *not* been reported previously; our observations were unique. Droplet lasing was measured at approximately 12 mm from the point of ignition except for the pentane/ethanol mixture, in which case the measurements were made at 10 mm. At approximately 15 mm from the point of ignition, the pentane/ethanol stream became unstable. Hence, the measurements were made far from this region. The burning rate constants found were 1.62×10^{-7}, 2.08×10^{-7}, and 7.28×10^{-7} $m^2\,s^{-1}$

for ethanol, methanol, and the pentane/ethanol mixture respectively. The D^2 law behavior of burning methanol droplets in a linear stream is illustrated in Fig. 3. Typical corresponding spectra for 3 consecutive methanol droplets are shown in Fig. 4. The blue shift in peaks with decreasing droplet diameter was very evident. The quality and hence accuracy of the spectra were excellent. The pentane/ethanol burning rate compared very well to the measurements of Silverman and Dunn-Rankin in hexane with a range of droplet spacings. The results of this study were presented at the Western States Meeting meeting of the Combustion Institute, Spring 1998. A paper describing the results has been accepted for publication in Combustion and Flame.

Computational Research

Navier-Stokes solver for the continuous phase

The Navier-Stokes solver for incompressible fluids requires a Poisson solver, which is one of the important features determining the performance of the solver. The Poisson equations for the complex-valued stream functions and the pressure modes are solved using one of two methods:

(1) LU-decomposition combined with deferred corrections to reduce the bandwidth of the coefficient matrix. The deferred corrections method for the 4[th] and higher order schemes is designed as iteration $\mathbf{X}^{n+1}=\mathbf{X}^n+\mathbf{M}^{-1}\mathbf{Q}^n$ where $\mathbf{Q}^n$ is the residual $\mathbf{Q}^n = \mathbf{R}-\mathbf{A}\mathbf{X}^n$. The original system is given by $\mathbf{AX} = \mathbf{R}$, where $\mathbf{A}$ and $\mathbf{R}$ are the coefficient matrix and the right side vector generated by the higher order finite difference schemes for the respective Poisson equations. The coefficient matrix $\mathbf{M}$ is constructed by using the second order discretization for the direction determining the bandwidth and the higher order schemes for the other direction. The convergence of this method is rapid; typically five to ten iterations are sufficient to drive the error to machine accuracy.

(2) Full Multi-Grid (FMG) method adapted for higher order finite-difference schemes. Several mesh levels are used in a W-cycle iteration starting with the solution on the coarsest mesh which is the LU decomposition method used in the first approach. Prolongation and restriction operators constructed for the Poisson equations in transformed coordinates and a red-black Gauss-Seidel smoothing method are used to compute the solution at all mesh levels. This method achieves better accuracy than method (1) in less CPU-time and requires significantly less memory.

PLES model for the particulate phase

A particle LES model (PLES) was developed and implemented into the LES code for the spatially developing turbulent round jet. The PLES model treats spherical subdomains $D_i(t)$ of the flow field with constant radius R containing $N_i(t)$ particles as an entity (called "blobs"), that is governed by dynamic equations for position and velocity similar to an individual particle. These equations contain additional terms representing the effect of particle motion inside the blob and the particles leaving and entering it.

The evolution of a blob $D_i(t)$ is determined by its centre location $\underline{X}'_i(t)$, the centre velocity $\underline{v}'_i(t)$ and the number of particles $N_i(t)$ in the blob. The velocity of a blob $D_i(t)$ changes with time according to $d\underline{v}'_i=\underline{P}_i dt+d\underline{Q}_i+ d\underline{S}_i+d\{d^2\underline{Y}/dt^2\}$ The forces acting on a blob are: $\underline{P}_i(t)$ is the particle force based on the centroid properties, $\underline{Q}_i(t)$ the difference between the average acceleration and $\underline{P}_i(t)$. The third contribution is due to the motion of particles through the spherical blob boundary and the motion of particles inside the blob. Closure models have been developed for $\underline{Q}_i$, $\underline{S}_i$ and $\underline{Y}$ based on integrated white-noise processes, which can be simulated using stochastic differential equations of the Ornstein-Uhlenbeck type.

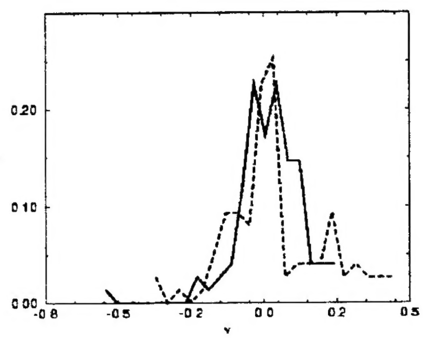

Figure 5 Pdf of blob (full line) and particle (dashed line) velocity component v at x/D = 8. Blobs and particles are released at the same locations and times.

Preliminary results are encouraging; the blobs follow roughly the cloud of particles they are designed to represent. The pdf of one of the Cartesian velocity components in the cross sections of a round jet at $\frac{x}{d}=8$ is shown in Fig. 5 for blobs (full line) and particles (dashed line). Each blob contains initially 100 particles, the evolution of the number $N^i(t)$ is simulated as an exponential decay using a constant time scale.

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Significant Interactions:

Transfer of details of droplet lasing spectroscopy experiments to Dr. Petra Staph of Daimler Benz Research Center, Stuttgart for comparison with numerical model of droplet vaporization in diesel sprays.

Inventions:

None